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ENGINEERING BY FUNDAMENTAL ELEMENTS OF EVOLUTION

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ABSTRACT

The method presented in this note mimics two fundamental mechanisms from nature, growth, and development, for the synthesis of new three-dimensional structures. The structures were synthesized to support a load generated by a wind. Every structure grows from a single artificial cell following a set of genes, encoded in an artificial genome shared by all cells. Genes are a set of commands that control the growth process. Genes are regulated by interaction with the environment. The environment is both external and internal to the structure. The performance each structure is measured by its ability to hold the load and other additional engineering criteria. A population of structures is evolved using a genetic algorithm, which alters the genome of two mating individuals. We will present evolved phenotypes with high degrees of modularity and symmetry which evolved according to engineering criteria. Neither one of these two characteristics has been directly imposed as the fitness evaluation, but rather spontaneously emerge as a consequence of natural selection. We will argue that the types of rules we are using in this model are not biased toward any of these characteristics, but rather basic rules for growth and development.

1 INTRODUCTION

The development of design synthesis methods has recently become an active area of research. The idea is to generate novel sets of design configurations that exhibit high performance properties. These designs may not be able to be created by an engineer using standard design techniques. An early contribution in this area [1] begins with engineering requirements and subdivides a given spatial domain into a fixed number of finite elements with well-defined boundary conditions. The optimization procedure finds the optimum structure by removing the lightly loaded elements leaving only those which form the optimum structure. A different approach [2] demonstrates a way to synthesize a compliant two-dimensional MEMS device by eliminating cells from a fixed mesh according to the evaluation of three parameters. From a mathematical point of view, both these methods find the optimum configuration from a finite set of configurations (large but still finite) determined by the initial mesh. This restriction dramatically limits the ability of each method to find a global optimum. Since, for a given design problem, the total number of possible configurations is generally infinite. Another disadvantage of using a fixed mesh is the inability to generate arcs and curved objects without using large number of elements. The method presented here addresses these issues using a different approach such that the space of possible configurations is infinite and the elements are not restricted to a single shape but are allowed to be deformed and differentiated. In this way smooth, curved, inhomogeneous structures can be synthesized.

Inhomogeneous structures can be useful in many areas including optics, mechanics, thermal management, etc. In optics, for instance, several layers of thin films create an optical filter. Each layer has different properties which makes the design of such filters highly complex. Different methods have been developed for the synthesis of such filters. J. Skaar [3] has shown a

way to synthesize optical thin-film filters with inhomogeneous properties such that each layer in the film has a different number of reflectors. Yang and Kao [4] introduced a way to evolve the structure of a thin film with inhomogeneous optical coatings such that the evolved structure has the functionality of a beam splitter and a narrow-band reflector. In all the described works, the genetic information contains a description of the individual (direct enconding), in contrast with indirect encoding, where the genetic information contains a set of rules that when executed (and perhaps influenced by various environmental factors) guide the growth and development of a single cell into an adult.

Indirect encoding, and the study of artificial embryogeny, has been proposed previously [5, 6, 7, 8]. Early work in this area has demonstrated the ability of indirect encodings to produce modular phenotypes in graphs and patterns [9, 10, 11].

The work presented here builds on these ideas, and demonstrates the unconstrained evolution of rules that produce structures comprising multiple materials (inhomogeneous), where fitness is determined only by structural performance. Biological structures are frequently inhomogeneous, and one of the main engineering functions of these structures is to maintain low mechanical stress when subjected to external loads [12]. An example of such structures are bones which are characterized by an ability to carry high dynamical loads but are still relatively light. The material structure of bones is highly complex which makes them difficult to be replicated with contemporary engineering techniques. The growth process of bones has been studied by several researchers who looked for the factors that stimulate growth. It was shown by Vander Sloten and Van Cleynenbreugel [13] that mechanical stress has a crucial effect on the behavior of bone cells during growth. They observed that under the influence of mechanical stress, bone cells tend to divide more rapidly than when unstressed.

The shape of biological structures has been an inspiration for an enormous number of designs [12]. The obvious example is aircraft that have topological similarity to birds. The precise process by which nature has been able to produce such high performance structures both in shape and in complexity is not yet fully known. However, it is well known that the building blocks of each biological structure are cells. During the growth and development process cells execute a set of steps encoded in an organism's DNA. These steps are controlled by genes, where each gene has different functionality. Once the individual has reach maturity the rate of the growth process is attenuated, and is ultimately stabilized in its final configuration.

Inspired by all of these ideas, a model has been implemented here which mimics some of the fundamental issues of biological growth and evolutionary processes. We have created a three dimensional evolutionary and development model for structures [14]. The structures (phenotypes) were evolved to hold an external load in the form of wind. The wind has been exerted randomly on the phenotypes during their growth process. Phenotypes which developed high stresses or phenotypes which were too heavy or both, received low fitness evaluations.

Our model contains artificial cells which are the building block of every phenotype. Cells in this model are an extended three dimensional finite element. In addition, every cell has an artificial genome that contains genes. Genes in our model can be interpreted as a *rule* set which is composed of two parts *if* condition - *then* action. The condition part usually relates to the "environment effects" which are sensed by the cells through chemical diffusion. The action part represents an operation , such as cell division, cell differentiation, cell adhesion, etc. Sections 1 through 3 of the paper start with a description of the model and will focus on the developmental process within the model. A description of the basic elements in the model will be given. These elements includes; genes, morphogens, signalling mechanisms, and the genome. We we will also briefly described two additional important mechanisms; diseases and metabolism. We will explain their necessity to the success of the model. Section 4 shows the phenotypes that were evolved in our model. We have simulated evolution and development of phenotypes that need to sustain loads generated by wind. We will show that the evolved phenotypes contain a high degree of modularity both in topology and in their internal structure. This problem has common roots both in the engineering and the biological worlds. In section 5 we will provide our conclusion and understanding based on the results.

2 Artificial Model

In the work reported here, an artificial model of structural growth has been created which is an extension of previous work done by the authors [14]. The two critical fundamental elements of this work are the selection of the artificial cell (the basic structural element) comprising each individual, and the artificial genes (the rules) which are evolved into the genetic information of each individual. The genetic information of an individual is shared by all of its cells. Each individual cell executes its rules until a mature structure is formed. Once maturity is reached, an evaluation scheme determines the fitness (performance) of the structure. Evolutionary operations (selection, crossover, and mutation) alter and refine genetic information in a population of individuals over multiple generations. The results are structures that meet the desired performance goals.

Mimicking nature, the basic structure of a gene is an *if*-conditional *then*-action rule. During the natural embryogeny of organisms like plants, every 3-D region can deform according to nine different geometric operations: one for isotropic growth, two for anisotropic growth (B), three for shear (S) and three for rotation [15], illustrated in Figure 1. In the artificial embryogeny presented here, the geometric operations (excluding the three for rotation) are defined as actions, and as with natural embryogeny, every geometric operation is assigned a unique alphabetic letter

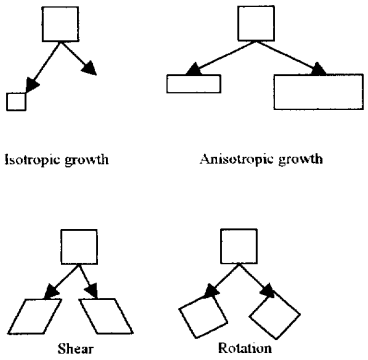

Figure 1. The four basic geometric operations observed in sub-regions of plants.

as shown in Table 4).

In addition to the geometric operation actions, cell-type actions are defined, as shown in Table 3. These actions are the three basic operations that occur in the developmental process of every biological structure, including; cell division, cell death, and cell differentiation. Cell division splits the cell into two equally sized cells, such that the total volume of the divided cells remains the same as that of the initial single cell. Cell death causes a cell to be removed from the model. Cell differentiation alters the material properties of a cell. All adjacent cells may communicate via protein diffusion. Proteins are generated by an execution of a protein gene("P"). Three parameters set the amount of protein, the protein's type and its concentration gradient. In this model there are currently four different type of proteins. The gradient is setup by specifying one the six faces of the cell as part of the gene syntax. By specifying a face the gradient determined between the center point of the cell and center point of the face. The concentration of proteins followed an exponential profile with respect to time 1. In our model cell's only respond to protein which were generated by their adjacent cells.

$$p = p_0 e^{-t}. \tag{1}$$

2.1 Environment

The environment in which the individuals are grown contains factors which every cell can sense and which may affect the way genes are expressed. The relationship between the information that cells receive from the environment and the development of the phenotype is not predetermined. Rather, conditionals are available to the evolutionary process that sense the concentration or gradient of each morphogen. In this way, the evolutionary process establishes the relationship between information, growth and development.

In the artificial embryogeny presented here, two kinds of morphogens are present. The first represents a source that drives the growth of the phenotypes toward it. This morphogen is produced continuously at a predefined location and diffuses through space, impinging on the walls of each cell. The second morphogen represents the surface of the ground to which cells adhere when they intersect the surface.

As the phenotype is being grown, it is evaluated by means of a finite element analysis to determine the pattern of mechanical stresses and deformations in the phenotype [16]. Every cell is an extended 3-D non-orthogonal finite brick element. Therefore, the structure and the mesh are identical, and are evolved simultaneously during growth and development. Cells also maintain information relating to their size, age, and distance from neighboring cells. Each type of information available to each cell is identified by a lower case alphabetic character, shown in Table 1.

Table 1. Cells Chemicals

ID	Description
a	Maximum principal stress normalized with the yield stress
b	Middle principal stress normalized with the yield stress
c	Minimum principal stress normalized with the yield stress
d	Principal vector correspond to the maximum principal stress
e	Principal vector correspond to the middle principal stress
f	Principal vector correspond to the minimum principal stress
g	Cell volume
h	Morphogen direction
i	Morphogen diffusion intensity
$p \times type \times face$	p - indicate protein, type - the type of protein (out of 4), face - the cell's face

2.2 Genome Structure

The genome contains words which contain genes with their corresponding letters (Tables 2 through 4). Every word starts with the letter "R" which indicates the number of times the particular word will be executed. The letter "Z" indicates the begin-

Table 2. Veto (conditional) genes

ID	Name	N^1	Possible Parameters
V	Suppress if below	1	$(a,b,c,g,i)\times$ fractional coefficient
W	Suppress if above	1	$(a,b,c,g,i)\times$ fractional coefficient

^1N =Number of Parameters

Table 3. Cell-type operation genes

ID	Name	N^1	Possible Parameters
D	Cell division	1	(d,e,f,h)
K	Cell death	0	
F	Cell differentiate	1	$(1,2,...^1n)$
P	Generate Protein	3	fractional coefficient$\times$ $(p)\times(f)$

^1N =Number of Parameters
^1n =Number of different cells
^1p =The type of protein (out of 4)
^1f =face number (out of 6)

Table 4. Geometrical operation genes

ID	Name	N^1	Possible Parameters
A	Shear	1	$(d,e,f,h)\times$ fractional coefficient
B	Anisotropic growth	3	$(a,b,c,g,i)\times$ fractional coefficient
C	Isotropic growth	1	$(a,b,c,g,i)\times$ fractional coefficient

^1N =Number of Parameters

ning of the word. The genes contain operations, parameters (*e.g., morphogen concentration or gradient*) and coefficients. Similar to transcription factors in nature, coefficients are numbers between zero and one, that scale an effect in proportion to the chemical to which they refer.

3 Control mechanisms

3.1 Conditionals

The conditional artificial genes are "veto" or "suppression" genes. These genes affect other genes only at the genome level, by turning actions off or on according to whether the conditional test is satisfied or not. This is shown in Table 2.

3.2 Metabolism and Thermodynamics

A thermodynamic energy consideration is present in the model which balances the maintenance of the organism mass with the creation of new mass [17]. The amount of energy, E_c, that each cell may consume, in a given time step, Δt, is proportional to its metabolic rate, B_c. Part of this energy is used for maintaining the existing phenotype while the remaining energy may be used for creation of new mass, as shown in Equation 2,

$$E_c = E_0 B_c \Delta t. \tag{2}$$

The cell's metabolic rate is proportional to the size of the phenotype S and can be determined using Kleinberg's law, given in Equation 3,

$$B_c \propto \frac{S^{3/4}}{N_c}. \tag{3}$$

Every gene's execution consumes energy. By specifying the amount of energy for every gene and by establishing E_0, a thermodynamic size limit can be specified for the phenotypes, as shown in Equation 4,

$$E_c = E_0 \frac{S^{3/4}}{N_c}. \tag{4}$$

The specification of energy needs to be determined by the user based on his experience with the model. Even when the phenotype reaches the thermodynamic limit, this approach will permit new mass to be created at the expense of removing existing mass, potentially changing the topology of the phenotype.

3.3 Diseases

A disease can only occur as a consequence of a defective genome. Examples of diseases in phenotypes include unlimited production of cells or production of cells that are significantly distorted. Once a disease has been detected, an artificial immune system attempts to eliminate it using several methods (*e.g.*, refining the mesh). If none of these methods work, the phenotype itself is eliminated, but not before it is evaluated and penalized for being incapable of reaching maturity.

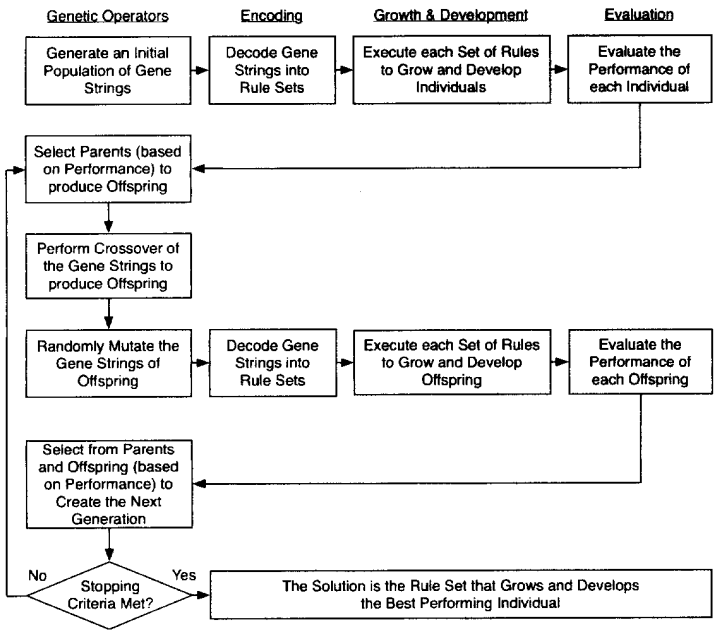

Figure 2. The computational evolutionary development process.

3.4 Evolutionary Scheme

The evolutionary scheme is derived from a genetic algorithm [18] with three steps: selection, crossover and mutation, and each repetition is defined as one generation. The algorithm is initialized with a set of randomly generated genomes. Starting from a single artificial cell, one individual is grown from each genome by executing the rules it contains. Once each individual reaches maturity, its fitness is evaluated by means of the finite element analysis and the aggregation of additional properties. The crossover operation is done only at the word's boundaries. The mutation rate is 1 which means that on the average every genome has a single mutation at every generation. A mutation can mutate an entire word or a single gene. Figure 2 show a flow chart which describes the evolutionary scheme.

4 Results

4.1 Configuration and synthesis of structures

The approach outlined above has been applied as an experimental representative of an important problem in engineering and nature. The problem was to synthesize the configuration of a structure to support a highly varied load generated by a wind. From a computational aspect we've used a very rough approximation which describes a structure subjected to a wind as shown in equation 5. The parameter F_i represents the load on node i, F_0 is the total maximum load on the entire structure, S is the structure's volume and N is the number of cells. Equation 5 shows that an increase in the total volume will results in an increase of the total load in an exponential manner, this behavior is roughly describes a structure which is subjected to a wind.

$$F_i = \frac{F_0\left(1 - \frac{1}{S^{1/3}}\right)}{N} \tag{5}$$

In addition, the structure needs to reach a certain height which increases simultaneously with the evolutionary process. For this problem, two morphogens are present in the environment. One morphogen represents a source that provides incentive for phenotypes to grow toward it. This source sets desired height of the structure. The other morphogen represents the ground. In addition to the two morphogens, the phenotypes are exposed to external forces. The first one is gravity, which is generated equally on the cells. The second force is similar to a force generated by wind, which is proportional to the projected area of the phenotypes. In our model, the wind is not constant but rather changes randomly during the growth process. Two kinds of materials may be utilized by the algorithms, representing steel and aluminum. The goal was to evolve phenotypes(structures) which utilized both material within a uniquely evolved topology. The fitness evaluation function was composed of six parameters: distance of the phenotype from the light source, age of the phenotype, weight, cell morphology, cell volume and the maximum mechanical stress on the cells. All of these parameters were aggregated to a single scalar through a unique aggregation function [19]. These parameters contains an important factors in engineering design such as weight, stress, volume etc. And also an important factors in biology such as age, distance and cell's morphology

Figure 3 shows six different phenotypes at different stages during the evolutionary process results from a single experiment. As we suspect each experiment will result in a different phenotype, as the number of "good" solution for this kind of problem is very high. We've decided to show here a single representative experiment. During the development process, the stresses and all other parameters are been calculated as the phenotype is constantly changes. However, the phenotype is not evaluate in terms of performance, this evaluation is only done at the maturity stage. The two phenotypes in Figure 3a and b correspond to an early stage of evolution. During this stage the target height of the phenotypes is relatively low (indicated by the pink region). This fact results in low bending stresses executed on the phenotype by the wind. We see that neither one of the phenotypes is modular and neither of them has a unique configuration. Nevertheless, the cells are subjected to low stresses, indicated by the green color. The four phenotypes in Figure 3c-f correspond to a late stage of the evolution. During this stage the target height of the phenotypes is high (indicated by the pink region). This fact results in high bending stresses, emerging in the phenotype caused by the wind. In Figure 3c the appearance of leg modules

can be identified. There are four legs with a bending shape connected to the ground. Two main characteristics are benefited by the evolution of legs; the first is low weight of the entire structure and the second is additional reinforcement. We want to emphasize that the rules on Table 1 through 4 are basic rules, none of which contain a set of instruction to generates legs. We can see that some of the cells in the phenotype are over stressed (red color). Figure 3d shows a phenotype similar to Figure 3c with an additional module that connects one of the legs to the middle part of the phenotype. The additional connection reduces the overall stresses on the phenotype. Figures 3e and f show a phenotype which contains the same leg modules as in Figures 3c and d but in a different configuration. From an engineering perspective this phenotype has classical engineering characteristics. It contains legs with radial symmetry which span a large base. The four legs converge quadratically toward a single module at the upper part of the phenotype. These configurations have high engineering properties such as strength and light weight. The evolution of symmetry is a very surprising result since non of the rules contains any type of hidden symmetry, yet the evolved phenotypes are symmetric.

5 Conclusion

A new method was presented which mimics two fundamental processes in nature; evolution and development for the synthesis of new three dimensional structures. An artificial model was setup with artificial cells containing an artificial genome. The genome contains sets of rules (genes), regulated by an external environment which grows a phenotype(structure) from a single cell. A set of rules has been carefully defined to describe the basic elements of growth and development. This set of rules is a non-biased set such that no hidden preference in the phenotype level exists. Phenotypes at the early stages of evolution contain very low degrees of modularity and are non-symmetric. Yet, these phenotypes are valid structures in terms of holding an external load, generated by the wind. During the late stages of evolution, high degrees of modularity and symmetry was identify in the phenotypes. The emergence of these characteristics occur spontaneously as a result of natural selection. We argue that the benefit of utilizing both modularity and symmetry by the phenotypes is due to their robustness. This result may shed a light on the emergence of modularity and symmetry in nature.

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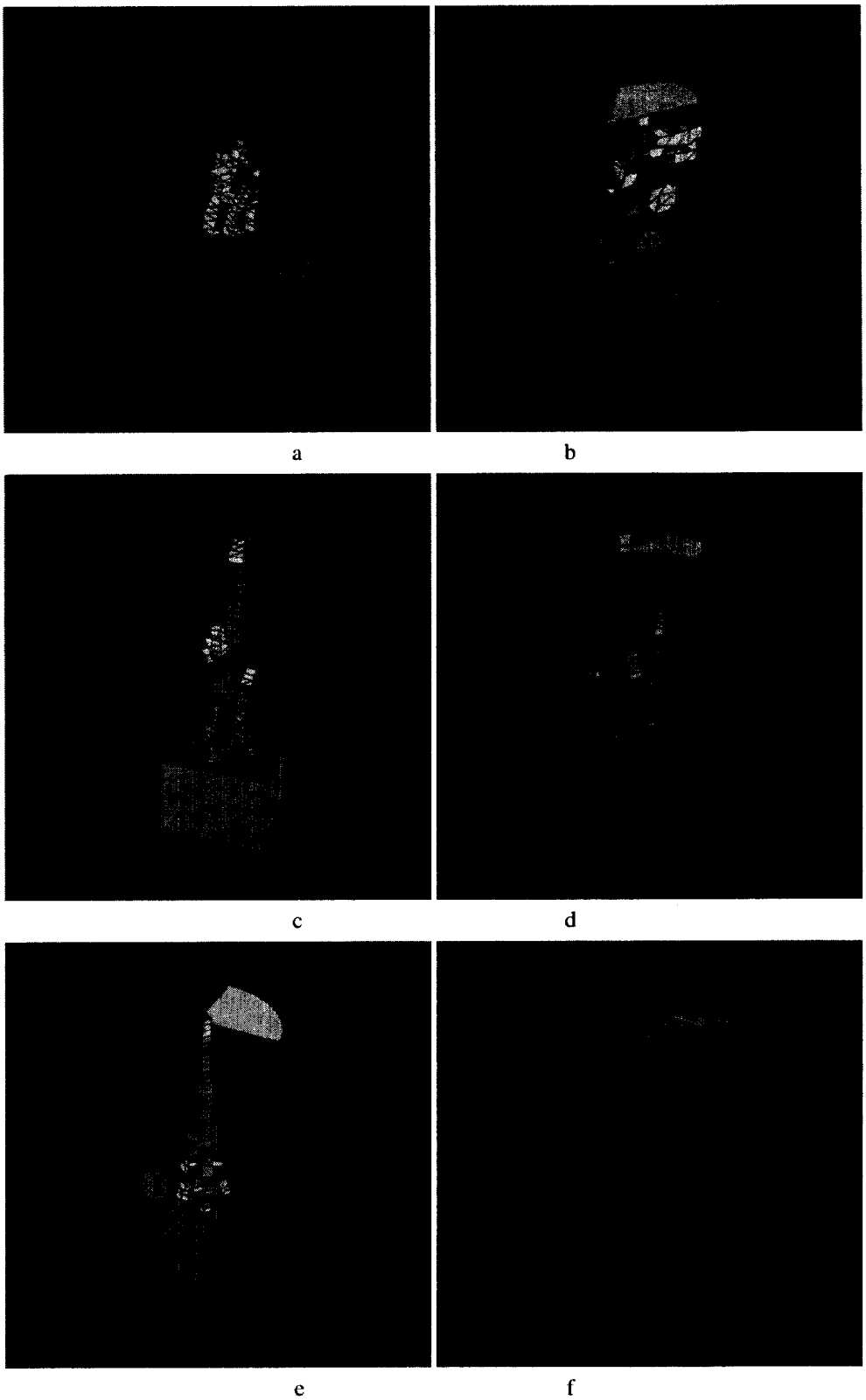

Figure 3. Six different generations - Six different stages during evolution with increasing order. The color of the cells represents their mechanical stress, the red color corresponds to high stress while the green color corresponds to low stress. a,b. 202,278 generations, low target height - the phenotype has no interesting configuration. c. 751 generations, high target height - Phenotypes which contains number of modules , cells are over stressed (red color) d. Similar configuration to (c) but additional reinforcements, non of the cell are over stressed. c. 812 generations - A new configuration of phenotype different from (c,d). d,e. 850generations the phenotypes becomes symmetric as the number of generations increases. f. 900 generations - The phenotype has a similar topology to a cone with four legs.

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